

# Noise properties of nanoscale YBCO Josephson junctions

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We present electric noise measurements of nanoscale biepitaxial  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (YBCO) Josephson junctions fabricated by two different lithographic methods. The first (conventional) technique defines the junctions directly by ion milling etching through an amorphous carbon mask. The second (soft patterning) method makes use of the phase competition between the superconducting YBCO (Y123) and the insulating  $\text{Y}_2\text{BaCuO}_5$  (Y211) phase at the grain boundary interface on MgO (110) substrates. The voltage noise properties of the two methods are compared in this study. For all junctions (having a thickness of 100 nm and widths of 250-500 nm) we see a significant amount of individual charge traps. We have extracted an approximate value for the effective area of the charge traps from the noise data. From the noise measurements we infer that the soft patterned junctions with a grain boundary (GB) interface manifesting a large c-axis tunneling component have a uniform barrier and a SIS like behavior. The noise properties of soft patterned junctions having a GB interface dominated by transport parallel to the ab-planes are in accordance with a resonant tunneling barrier model. The conventionally patterned junctions, instead, have suppressed superconducting transport channels with an area much less than the nominal junction area. These findings are important for the implementation of nanosized Josephson junctions in quantum circuits.

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## I. INTRODUCTION

Micrometer-sized grain boundary (GB) Josephson junctions (JJs) made of High Critical Temperature Superconductors (HTS) are commonly used for the realization of superconducting devices operated in a wide temperature range up to the boiling temperature of liquid nitrogen. A prominent example is the Superconducting QUantum Interference Device (SQUID) for sensitive magnetic flux detection [1]. Nevertheless, GB JJs are still a fundamental tool for the exploration of the complex physics inherent to HTS materials [2–6]. Their implementation in superconducting circuits operated in the quantum limit, such as quantum bits or single electron transistors, are expected to give further useful hints on the unresolved nature of superconductivity in HTS materials [7]. Recent advances in the thin film technology and nano-fabrication of HTS made it possible to observe macroscopic quantum phenomena in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (YBCO) biepitaxial grain boundary Josephson junctions [5, 6] opening the way for the realization of HTS quantum circuits. For typical JJ-based devices, which operate in the quantum limit (typically at temperatures below 100 mK), the requirements on junction

critical currents and capacitances are met for lateral dimensions on a length scale of 100 nm [7, 8].

The realization of reproducible HTS JJs at the nanoscale can also be instrumental to fabricate sensors with a quantum limited sensitivity like nano-SQUIDs, which can allow the detection of magnetic nano-particles in a much wider temperature and magnetic field range compared to its low critical temperature superconductor (LTS) counterpart.

In this respect it is of particular importance to understand the microscopic properties and dynamics of charge transport across nano-sized GB JJs. Here, the investigation of low frequency electric noise is a very useful tool to study the dynamics of both cooper pair and quasi-particle charge transport, revealing among other things information about the nature of the GB interface and its homogeneity. Still after numerous experimental studies on HTS GB junctions during the last decades the underlying physical transport mechanisms across the GB interface are subject of recurring discussion.

A large number of noise studies have been performed on wide bicrystal and biepitaxial GB JJs with junction widths ranging from one to several tens of micrometers [9–14]. Only a few electric transport studies have been performed on sub-micrometer bicrystal GBs, where single charge trapping states, responsible for the low frequency fluctuations of the transparency of the GB barrier, could be resolved [15].

In this article we compare two methods to fabricate YBCO Josephson Junctions at the nano scale and their respective noise properties. These methods are based on biepitaxial grain boundaries created in single layer YBCO films. Both a conventional technique, where the nanosized junctions are patterned by electron beam lithography and ion milling, and a new technique, where

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the junctions are formed as a result of phase competition between superconducting and insulating phases at the grain boundary interface, will be described. We have previously shown that the two methods give Josephson junctions with fundamentally different critical current density  $j_C$  and resistivity  $\rho_N$  values[16]. In this paper we compare the noise data of soft nanopatterned GB junctions to various electrical transport models, which allows us to determine the nature of the biepitaxial GB barriers. Moreover, from the analysis of single charge trap states in the GB barriers we are able to qualitatively and quantitatively assess the detrimental effect of ion milling on GBs during the conventional fabrication.

This paper is organized as follows. In section II we describe both the conventional and soft nano-structuring of biepitaxial YBCO JJs. Section III is dedicated to the comparison of the dc transport properties between junctions fabricated with the two nano-patterning methods. The noise models applicable to GB JJs are introduced in section IV. In section V we present the results and discussion of noise measurements on JJs fabricated with the two nano-lithographic methods.

## II. SAMPLE FABRICATION

### A. Conventional nanostructuring

The conventional way to fabricate deep submicron biepitaxial Josephson junctions is to use electron beam lithography in combination with a hard mask and ion beam milling. This procedure, with amorphous carbon as hard mask, is well established and has been proven to work well for the realization of various kinds of submicron HTS Josephson junctions, for example ramp type[17], bicrystal[18] and biepitaxial[19]. In this work we have fabricated deep submicron Josephson junctions by the biepitaxial technique. Details on the fabrication procedure can be found elsewhere[19, 20]. Here we only summarize the main steps. First a 30 nm thick SrTiO<sub>3</sub> (STO) layer is deposited on a MgO (110) substrate using Pulsed Laser Deposition (PLD). Next an amorphous carbon mask is deposited and then patterned using e-beam lithography and oxygen plasma. Part of the seed layer is then removed using Ion milling. Then a 100-120 nm thick YBCO film is grown by PLD at a temperature of 790°C. The film will grow (001) oriented on the MgO substrate and (103) on the STO seed layer. The YBCO film is then patterned using ion milling through an amorphous carbon mask defined by e-beam lithography. Even though junctions with widths smaller than 100 nm can, in principle, be fabricated with this procedure, the damage caused by the ion milling process will effectively limit the smallest possible width. The damaged grain boundary region on both sides of the junction constitutes a significant part of the total junction width, which strongly affects the superconducting properties. We have therefore engineered an alternative way to nanostructure HTS

Josephson junctions, which is described in the following section.

### B. Soft nanostructuring

We have developed a new soft patterning method that allows fabricating biepitaxial grain boundary junctions at the nanoscale without significant lateral damaging effects due to the ion milling. The procedure is based on the competition between the nucleation of the superconducting and insulating phases at the grain boundary. To fabricate the junctions we use the fact that for certain deposition conditions secondary insulating phases like Y<sub>2</sub>BaCuO<sub>5</sub> (Y211, also called greenphase) can nucleate on MgO(110) in addition to the superconducting YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7- $\delta$</sub>  (Y123). The amount of greenphase increases for non optimal deposition conditions and in the presence of grain boundaries[8, 21, 22]. Nano sized superconducting Y123 connections embedded in a greenphase matrix are expected to be formed at the grain boundary, see Figure 1 (a). These connections can be isolated using a Focused Ion Beam (FIB), see Figure 1 (b) and (c).

We first fabricate 10  $\mu$ m wide grain boundary junctions using the conventional method. A deposition temperature of 740°C is used for the YBCO film. The grain boundary is then examined using atomic force microscopy (AFM) and scanning electron microscopy (SEM). A suitable superconductive nanoconnection is selected and then isolated by using FIB. By leaving greenphase regions of at least 300 nm on each side of the Y123 connection, nanosized Josephson junction with no lateral damage are created since the Ga ions will only get implanted into the greenphase layer. Figure 1 (c) shows a final device, where we have isolated an approximately 200 nm wide junction protected on both sides by greenphase.

## III. COMPARISON BETWEEN THE TRANSPORT PROPERTIES OF CONVENTIONAL AND SOFT NANOPATTERNED JUNCTIONS

Electrical properties such as critical current density ( $j_C$ ), specific resistance ( $\rho_N$ ) and critical current ( $I_C$ ) vs magnetic field ( $B$ ) have been extensively examined[16] and have shown significant differences for the two fabrication methods. Figure 2 shows the current voltage characteristics (IVC) for (a) a soft nanopatterned junction (200 nm wide), (b) a 300 nm wide conventionally patterned junction and (c) a 200 nm wide conventionally patterned junction. A recurring pattern is seen here: the soft nanostructured junctions have an order of magnitude or more higher  $j_C$  and one or several orders of magnitude lower  $\rho_N$  when compared to conventionally fabricated samples. Conventionally fabricated junctions with a width of 200 nm or less have high resistive non-linear IVCs with a suppressed Josephson current. Only

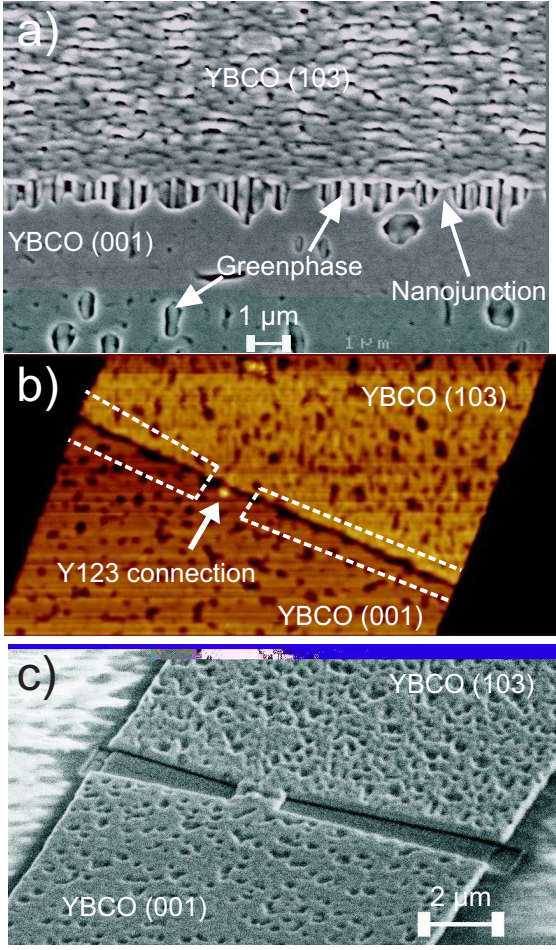


FIG. 1: (a) SEM image of an interface between a (001) and (103) YBCO film. A significant amount of greenphase is present near the grain boundary. In a different study[16] transmission electron microscopy and energy dispersive x-ray analysis was used to confirm that the precipitate at the grain boundary is greenphase. (b) AFM scan of a 10  $\mu\text{m}$  wide grain boundary interface before the FIB procedure. (c) SEM image of the same interface after the unwanted YBCO have been removed by the FIB leaving only one or two connections.

junctions with widths 300 nm or more showed a Josephson current.

$I_C$  vs  $B$  measurements revealed significant differences in the modulation period for the two fabrication methods. The period of the magnetic field modulation ( $\Delta B$ ) of the Josephson current can be used to approximate the width ( $w$ ) of the region exhibiting Josephson coupling in the junctions. Figure 3 (a) shows the  $I_C$  vs.  $B$  for a 10  $\mu\text{m}$  wide grain boundary junction before the FIB cut to isolate the nanojunction; The behavior of the magnetic pattern is that of several parallel junctions[23, 24]. Figure 3 (b) shows the magnetic pattern of a softpatterned junction after the FIB cut, leaving only one or two connections.

Depending on the electrode geometry we use the two expressions for  $\Delta B$  as a function of the junction width

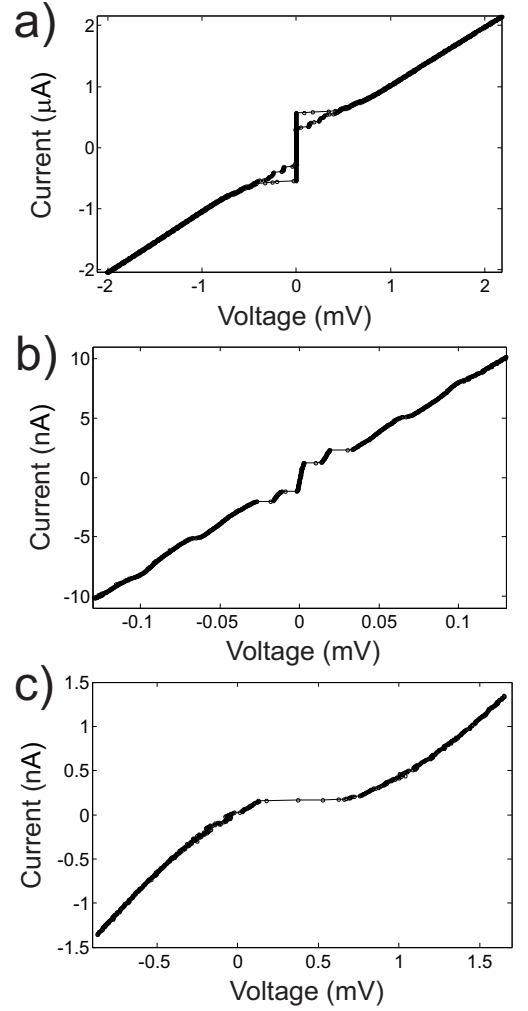


FIG. 2: Current voltage characteristics for (a) A nanojunction fabricated using the soft nanopatterning technique. The width of the junction extracted from AFM is 200 nm. (b) a sample fabricated with the conventional nanopatterning technique. The second switch is because this specific sample was designed to have 2 Josephson junctions in series to allow study of charging effects. Here the nominal junction width is 300 nm. (c) A sample fabricated using the conventional method, 200 nm wide, with a coulomb blockade like behavior and no critical current. The measurements were done at 271, 16 and 22 mK, respectively.

$w_j$  from Rosenthal and coworkers[40][25]: For the soft patterned junctions having wide electrodes  $w_e \simeq 10\mu\text{m}$  we use the thick electrode limit expression

$$\Delta B = \frac{\Phi_0 t}{1.2 w_j^2 (\lambda_{103} + \lambda_{001} + d)} \quad (1)$$

valid for  $\lambda_{001,103}^2/t < w_e$ . Here  $\lambda_{001}$  and  $\lambda_{103}$  are the London penetration depth in the (001) and (103) electrode, respectively.  $\Phi_0$  is the magnetic flux quantum,  $t$  is the thickness of the film and  $d$  is the thickness of the junction barrier. For the conventionally nanopatterned junctions the width of the electrodes is equal to the width of the

junctions  $w_e \simeq 300 - 500$  nm. Here the thin electrode limit ( $\lambda_{001,103}^2/t \geq w_e$ ) applies

$$\Delta B = \frac{1.84\Phi_0}{w_j^2}. \quad (2)$$

The London penetration depth in the (001) electrode is given by the penetration depth in the ab-planes  $\lambda_{001} = \lambda_{ab}$ . Instead, as a result of the London penetration depth anisotropy in YBCO  $\lambda_{103}$  is given by a combination of  $\lambda_{ab}$  and the c-axis penetration depth  $\lambda_c$ , which depends on the grain boundary angle[4][41].

Equation 1 was used on a number of soft patterned junctions and the extracted width was compared to the nominal width measured by AFM and SEM[16]. The values were at most differing by 40%; This shows that the width of the superconducting transport channels extracted from the magnetic pattern was very close to the measured junction widths.

For one of the conventionally nanopatterned junction a  $\Delta B$  of approximately 1 T was extracted from the magnetic pattern. Using equation 2 resulted in a width of 60 nm, significantly less than the nominal junction width of 300 nm. Similar results were obtained for two other junctions 300 and 500 nm wide. This in combination with the  $j_C$  and  $\rho_N$  values shows that a substantial part of the grain boundary, approximately 100 nm wide, on each lateral side of the junction does not feature any Josephson coupling.

The magnetic patterns of conventionally nanopatterned junctions have revealed the presence of a highly non uniform grain boundary, having a much reduced region with Josephson coupling compared to the nominal one. However, this does not give a clear image of the total area which retains the Josephson coupling along the grain boundary. In fact, it only tells us that the largest spacing between superconducting channels is significantly less than the nominal junction width. To estimate the area of both the Cooper pair and quasiparticle transport channels we analyzed the voltage noise of the junctions caused by single charge traps in the GB barrier, which will be discussed in section V.

#### IV. NOISE THEORY FOR GRAIN BOUNDARY JUNCTIONS

Noise measurements are a helpful tool to extract information about the electrical transport through the junction and hence to obtain information about the nanostructure of the grain boundary interface. In this work we focused on the low frequency noise spectra of both the critical current fluctuations  $\delta I_C$  and normal resistance fluctuations  $\delta R_N$ , which are related to the transport mechanisms of the cooper pairs and quasiparticles, respectively.

It is well established that at low frequencies the critical current and normal resistance fluctuations are governed

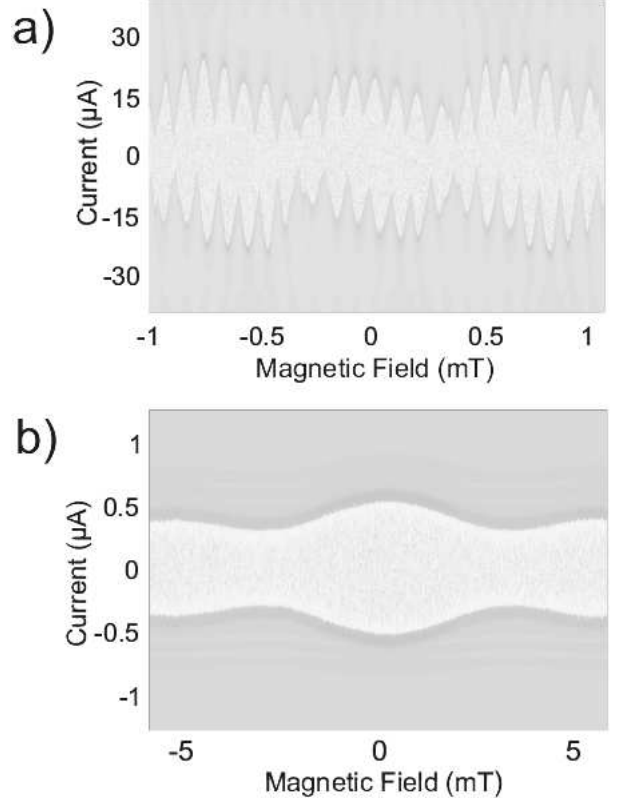


FIG. 3: I vs B for (a) a 10  $\mu\text{m}$  wide grain boundary with many parallel channels. (b) a sample cut by FIB, which consists of only 1 or 2 parallel channels. The grey scale represents the logarithmic conductance and the darkest region corresponds to  $I_C$ .

by bistable charge trapping states in the junction barrier [27]. The trapping of a charge will locally increase the junction barrier making it less transparent. This process can be considered as a reduction of the total junction area  $A_j$  by an amount which is proportional to the cross section of the localized charge trap state  $A_t$ . The fluctuating barrier transparency (or equivalently junction area) results in fluctuations of the critical current  $I_C$  and normal resistance  $R_N$ . Each individual charge trap causes a random telegraph switching (RTS) signal between two states, with respective mean lifetimes  $\tau_1$  and  $\tau_2$ , of both the junction normal resistance and critical current. The corresponding frequency spectrum is given by a Lorentzian [28]:

$$\begin{aligned} S_R^{RTS}(f) &= \frac{4\langle(\frac{\delta R_N}{R_N})^2\rangle\tau_{eff}}{1 + (2\pi f\tau_{eff})^2}, \\ S_I^{RTS}(f) &= \frac{4\langle(\frac{\delta I_C}{I_C})^2\rangle\tau_{eff}}{1 + (2\pi f\tau_{eff})^2}, \end{aligned} \quad (3)$$

where  $\tau_{eff} = (\tau_1^{-1} + \tau_2^{-1})^{-1}$  is the effective lifetime of the underlying RTS signal and  $f$  is the frequency.  $\langle(\delta R_N/R_N)^2\rangle$  and  $\langle(\delta I_C/I_C)^2\rangle$  are the mean squared rel-

active fluctuations of the normal resistance and critical current caused by the charge trap. For large enough junction areas many bistable charge trapping states will contribute to the total noise. Assuming a constant distribution of transition rates  $1/\tau_{eff}$  the resulting noise power spectrum will have a  $1/f$  shape.

The values of the relative root mean square (rms) fluctuations  $\delta I_C/I_C$  and  $\delta R_N/R_N$  can be determined by measuring the voltage noise across the junction at various bias current values. For a Josephson junction having a non hysteretic current voltage characteristic the total voltage fluctuations across the junction at a fixed bias current  $I$  are given by [10]

$$S_V(f) = (V - R_d I)^2 S_I(f) + V^2 S_R(f) + k(V - R_d I) V S_{IR}(f), \quad (4)$$

where  $V$  is the dc-voltage across the junction,  $R_d = \partial V / \partial I$  is the differential resistance,  $S_I = |\delta I_C / I_C|^2$ ,  $S_R = |\delta R_N / R_N|^2$ , and  $S_{IR} = |\delta I_C / I_C| |\delta R_N / R_N|$  is the cross spectral density of the fluctuations. Here it is assumed that  $S_I$  and  $S_R$  are composed of an ensemble of RTS signals,  $S_I^{RTS}$  and  $S_R^{RTS}$ , respectively. The value  $k$  represents the correlation between the  $\delta I_C$  and  $\delta R_N$  fluctuations. One has  $k = -2$  and  $k = 2$  for perfectly antiphase and inphase correlated fluctuations, respectively. For uncorrelated fluctuations one obtains  $k = 0$ . From equation 4 it follows that at bias currents close to the critical current the voltage fluctuations are dominated by critical current fluctuations  $S_I$  due to the large differential resistance. For large bias currents, where the differential resistance approaches the asymptotic normal resistance, the voltage noise is governed by resistance fluctuations  $S_V = V^2 S_R$ . The correlation term  $S_{IR}$  will only contribute to the voltage noise in the intermediate bias current regime, while it is negligible close to the critical current and for large bias currents.

The values of the relative fluctuations  $\delta I_C / I_C$  and  $\delta R_N / R_N$  depend on the nature of the junction barrier. Indeed, from the ratio  $q = |\delta I_C / I_C| / |\delta R_N / R_N|$  between the relative fluctuations one can extract information about the homogeneity of the junction barrier as we will discuss on the basis of the following three junction models applicable to grain boundary junctions:

For a homogenous junction barrier one can assume that the  $I_C R_N$  product is a constant, independent of the critical current density  $j_c$  and resistivity  $\rho_n$ . This is for example the case for a superconductor-insulator-superconductor (SIS) junction [23], where cooper pairs and quasiparticles tunnel (directly) through the same parts of the junction. From the constant  $I_C R_N$  product it follows directly that the relative fluctuations of the critical current and normal resistance have the same amplitude and are anticorrelated  $\delta I_C / I_C = -\delta R_N / R_N$ , resulting in a ratio  $q = 1$ .

In the Intrinsic Shunted Junction (ISJ) model [29, 30], instead, where the barrier is assumed to be inhomogeneous containing a high density of localized electronlike states, the quasiparticle transport is dominated by resonant tunneling via the localized states. On the contrary,

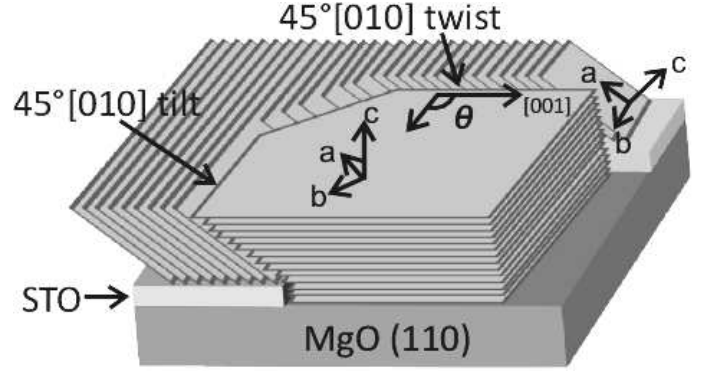


FIG. 4: a) Sketch of the interface geometry. The crystallographic orientations of the (001) and (103) YBCO is indicated by arrows.  $\theta$  is the interface angle and is defined with respect to the [001] MgO direction.

due to Coulomb repulsion cooper pairs can only tunnel directly through the barrier. Detailed calculations show that the  $I_C R_N$  product is not anymore constant, instead it follows the scaling behavior  $I_C R_N \propto (j_c)^p$ , where  $j_c$  is the critical current density of the junction and  $p$  is a constant depending on the position of the localized states. For localized states sitting in the middle of the barrier the scaling power is  $p = 0.5$ . From this  $I_C R_N$  scaling behavior one obtains for the ratio of the normalized fluctuations  $|\delta I_C / I_C| / |\delta R_N / R_N| = q = 1 / (1 - p)$  [29]. Typical experimental values of  $q$  range between 2 and 4 [9, 11–13].

The channel model proposed by Micklich *et al.* [10] assumes a junction which consists of  $N$  parallel channels, where all channels have the same resistance but only one channel carries a supercurrent. For a large number of channels  $N$  the fluctuations in critical current can be much higher than the fluctuations in resistance, giving a high ratio  $q$ . Since the supercurrent and the quasiparticles have separate channels no correlation between the critical current and resistance fluctuations is expected.

## V. RESULTS AND DISCUSSION

The voltage noise spectral density was measured using a room temperature voltage preamplifier with an input noise of  $4 \text{ nV/Hz}^{1/2}$  followed by a Stanford Research Dynamic Signal analyzer SR785 for a number of bias points. These measurements were done at 4 K for the soft nanostructured junctions, where the current voltage characteristic was non hysteretic. For the conventionally fabricated samples a temperature of 280 mK was needed to avoid thermal smearing of the IVC (due to the low  $I_C$  of these junctions) [10].

All noise measurements on the conventionally patterned samples refer to grain boundaries obtained by patterning the STO seed layer parallel to the [100] direction ( $\theta = 0^\circ$ ) of the MgO substrate [4] (see Fig. 4). The soft patterned junctions had nominal interface an-

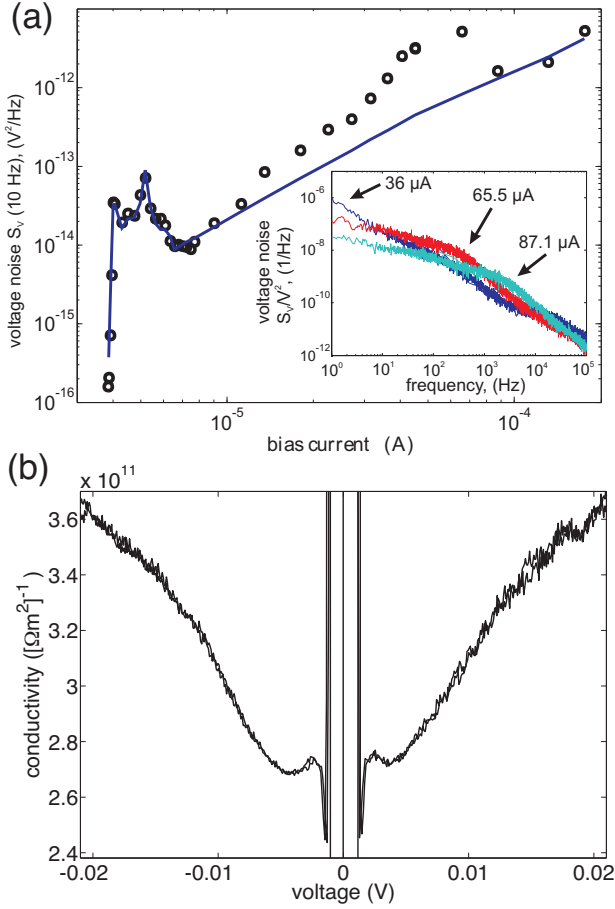


FIG. 5: (a) Voltage noise at 10 Hz as a function of bias current (open symbols) for a soft nano patterned junction (nominal interface angle =  $30^\circ$ ). A theoretical fit (solid line) is included to determine  $S_I$  and  $S_R$ . The inset shows the voltage noise as a function of frequency for three different bias points. The "hump" moves to higher frequencies when the bias is increased. (b) Conductivity as a function of bias voltage of the soft nano patterned junction. The central part ( $|V| < 1$  mV) is related to the Josephson effect.

gles ( $\theta$ ) of  $30^\circ$  and  $50^\circ$ . Grain boundaries with a small interface angle  $\theta$  have a micro structure close to a basal-plane like type ( $45^\circ$  [010] tilt), see Fig. 4, where the a-b planes of the (001) YBCO electrode meet one single a-b plane on the (103) YBCO electrode side[31]. These grain boundaries have proven to be low dissipative [5, 6, 32] compared to [001]-tilt ones and suitable for applications in quantum circuitry. By increasing the GB angle  $\theta$  the interface gradually evolves into a  $45^\circ$  [010] twist GB at  $\theta = 90^\circ$  (see Fig. 4).

#### A. Noise properties of soft patterned junctions

In Figure 5 (a) the voltage noise spectral density at 10 Hz is plotted as a function of the bias current  $I$  for one of our soft patterned nanojunctions having a width

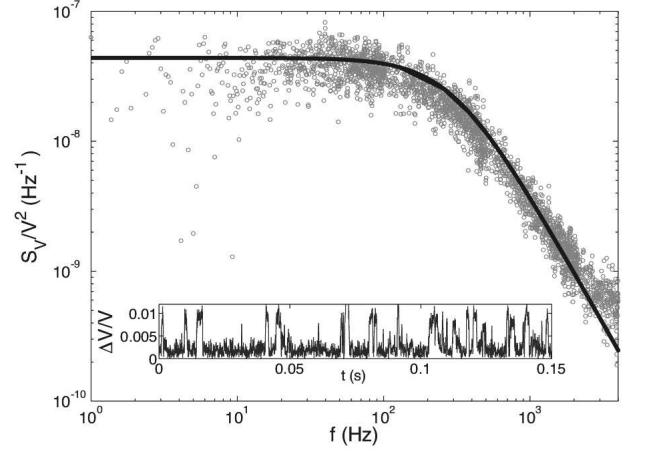


FIG. 6: Noise spectrum measured at  $I \gg I_C$  after the subtraction of the  $1/f$  background. The black line is a Lorentzian fit to equation 7. The plateau of the Lorentzian is given by  $4\tau_{eff}\langle(\delta V/V)^2\rangle$ , with  $2\pi\tau_{eff} = 302$  Hz and  $\delta V/V = 0.0044$ . The inset shows the respective time trace with  $\Delta V/V \simeq 0.0095$ .

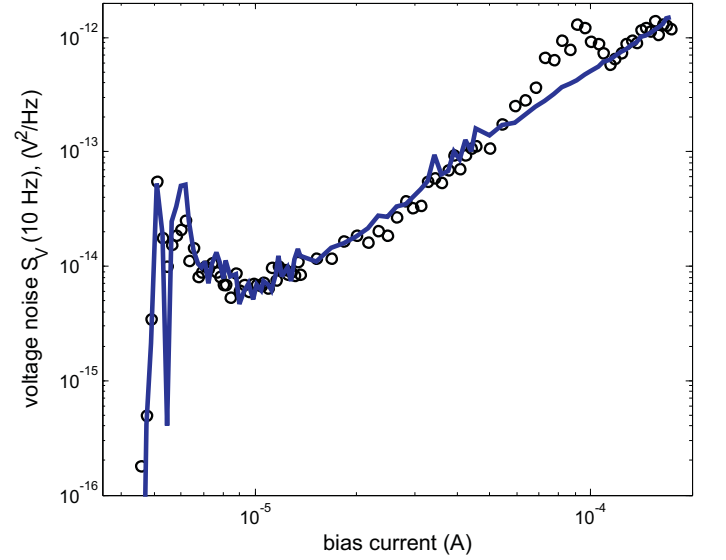


FIG. 7: Voltage noise at 10 Hz as a function of bias current (open symbols) of a soft nano patterned junction with an interface angle of  $50^\circ$ . The solid line is a theoretical fit used to determine  $S_I$  and  $S_R$ .

$w \simeq 200$  nm and nominal interface angle of  $30^\circ$ . However, by examining the grain boundary by AFM the actual interface angle was closer to  $0^\circ$ .

As expected, the noise peaks close to the critical current when  $I \simeq I_C = 4 \mu\text{A}$ . A second peak appears close to  $I = 5.2 \mu\text{A}$ . This is due to a resonance feature in the IVC causing the differential resistance ( $R_d$ ) to spike. For higher bias, where the resistance fluctuations dominate, the noise increases quadratically. The hump structure around  $50 \mu\text{A}$  is caused by a single charge trap causing a



TABLE I: Collection of  $1/f$  noise in HTS GB Josephson junctions of different HTS material, GB interface type, technology, and junction area  $A_j$ . The interface angle  $\theta$  of the soft patterned junctions is illustrated in Fig. 4. The values  $\alpha$  and  $\beta$  are given by  $\cos^2(2\pi\theta/360)$  and  $\sin^2(2\pi\theta/360)$ , respectively.

Junction technology	GB type	$A_j$ ( $\mu\text{m}^2$ )	$S_I^{1/2}$ (10 Hz) $\times 10^{-4}(\text{Hz}^{-1/2})$	$q = (S_I/S_R)^{1/2}$	$A_j^{1/2} S_I^{1/2}$ (10 Hz) $\times 10^{-6}(\mu\text{m}/\text{Hz}^{1/2})$
YBCO/STO/MgO biepitaxial $\theta \simeq 0^\circ$ (this work)	$45^\circ$ [010] tilt	0.02	$1.0 \pm 0.1$ ( $T = 4.2\text{K}$ )	$1.0 \pm 0.1$	14
YBCO/STO/MgO biepitaxial $\theta \simeq 50^\circ$ (this work)	$\alpha \cdot \{45^\circ$ [010] tilt $\} +$ $\beta \cdot \{45^\circ$ [010] twist $\}$	0.052	$1.6 \pm 0.1$ ( $T = 4.2\text{K}$ )	$1.8 \pm 0.2$	36
YBCO/NdGaO <sub>3</sub> bicrystal (Ref. [14])	$2 \times 14^\circ$ [100] tilt	0.06	$0.36 \pm 0.06$ ( $T = 55\text{K}$ )	$1.05 \pm 0.1$	10
YBCO/STO bicrystal (Ref. [9])	$25^\circ$ [001] tilt	1.0	0.32 ( $T = 70\text{K}$ )	2.5	32
Bi <sub>2</sub> Sr <sub>2</sub> CaCu <sub>2</sub> O <sub>8+x</sub> /STO bicrystal (Ref. [11])	$24^\circ$ [001] tilt	1.6	$0.24 \pm 0.06$ ( $T = 40 - 70\text{K}$ )	$1.9 \pm 0.3$	30
YBCO/STO bicrystal (Ref. [12, 13])	$24^\circ$ [001] tilt	3.8	$0.18 \pm 0.01$ ( $T = 25 - 70\text{K}$ )	$3.8 \pm 0.6$	35
YBCO/STO bicrystal (Ref. [12, 13])	$36.8^\circ$ [001] tilt	1.0	$0.35 \pm 0.12$ ( $T = 30 - 70\text{K}$ )	$3.7 \pm 0.8$	35

RTS signal with a typical Lorentzian spectrum on top of a  $1/f$  background. The occurrence of such Lorentzians is typical for a limited number of charge traps in submicron sized GB junctions [15]. The voltage dependence of the effective lifetime of the charge trap causes the Lorentzian to move to higher frequencies for increasing bias current, which is shown in the inset of Figure 5.

To fit the measured voltage noise spectral density at 10 Hz as a function of bias current (see solid line in Figure 5 (a)) to equation 4, which assumes a pure  $1/f$  noise spectrum, we neglected the data between 20  $\mu\text{A}$  and 80  $\mu\text{A}$  caused by a single charge trap. From the fit we obtain  $S_I \simeq S_R \simeq 10^{-8}/\text{Hz}$  resulting in  $q = |\delta I_C/I_C|/|\delta R_N/R_N| \simeq 1$ , and  $k \simeq -1.3$ . The ratio  $q \simeq 1$  indicates that our junction has a rather homogeneous barrier, where quasi particles and Cooper pairs tunnel directly through the same parts of the barrier [10]. Together with a tunnel like conductance spectrum (see Figure 5 (b)) we can conclude that our junction barrier is very similar to that of a SIS junction, consistent with the band bending model [33, 34]. Similar results have only been found in  $2 \times 14^\circ$  [100]-tilt YBCO GB Josephson junctions [14]. Furthermore, our result is incompatible with the Intrinsically shunted junction model [11, 12, 29, 30] and the channel model [10], where  $q$ -values larger than 2 are expected. The deviation of the correlation between the critical current and resistance fluctuations from perfect anti-correlation ( $k = -2$ ) could be caused by the limited amount of two level fluctuators in the small junction area not representing a perfect ensemble.

It is important to point out that the noise properties of our nano junction close to an ideal SIS Josephson junction underline once more the pristine character of the junction barrier that can be obtained by using the soft nano-patterning method.

In Figure 7 the voltage noise spectral density at 10 Hz is plotted for a 520 nm wide sample having a nominal interface angle of  $\theta \simeq 50^\circ$ . This value was confirmed by the AFM inspection of the GB. From the fit we obtain  $S_I \simeq 2 \cdot 10^{-8} - 3 \cdot 10^{-8}/\text{Hz}$ ,  $S_R \simeq 8 \cdot 10^{-9}/\text{Hz}$ , and  $k \simeq -0.5$  resulting in  $q = 1.8 \pm 0.2$ . The  $q$  value close to 2 indicates that the transport across the GB barrier cannot be described by a direct tunneling model, e.g. a homogeneous SIS tunnel junction. Instead, our result shows that for this kind of GB type (mixture of  $45^\circ$  [010] twist and  $45^\circ$  [010] tilt) the barrier is better described by the ISJ model, where quasiparticles tunnel resonantly via localized states.

In table I we summarize the noise data of the soft nanopatterned biepitaxial YBCO GB junctions together with results from literature on HTS Josephson junctions of various GB types. Comparing the ratios  $q = (S_I/S_R)^{1/2}$  between different GB types one can clearly see that only GBs where the ab-planes in at least one of the electrodes are tilted around an axis parallel to the GB interface, e.g.  $45^\circ$  [010] tilt (this work) and  $2 \times 14^\circ$  [100] tilt [14], have a ratio  $q \simeq 1$ . All the other GB types such as [001] tilt [9, 11–13] and  $\alpha \cdot \{45^\circ$  [010] tilt $\} + \beta \cdot \{45^\circ$  [010] twist $\}$ , with  $0 < \beta \leq 1$  exhibit ratios  $q \gtrsim 2$ . These facts give a strong indication that the nature of HTS GB

barriers depends on how the ab-planes meet at the interface. GBs with ab-planes tilted around an axis parallel to the GB interface, such as a basal plane GB, can be described by a direct tunneling model consistent with a homogeneous SIS barrier. All other GB types deviating from a bare rotation of the ab-planes around the GB line are characterized by resonant quasiparticle tunneling via localized states (ISJ model).

From the spectral density of the critical current fluctuations and the junction area one can obtain information about the areal charge trap density  $n_t$  and the cross sectional area  $A_t$  of the charge traps [37, 38]. Assuming  $N$  identical and independent charge traps the spectral density of the relative critical current fluctuations scales with the junction area  $A_j$  as  $\langle(\delta I_C/I_C)^2\rangle = N(A_t/A_j)^2 = n_t A_t^2/A_j$ . From this equation it follows that the quantity  $(S_I A_j)^{1/2}$  is proportional to the product of cross sectional area of a charge trap and the square root of the trap density  $A_t n_t^{1/2}$ . In table I we show the computed product  $(S_I A_j)^{1/2}$  at 10 Hz for the various GB types. Remarkably the values for GBs having ratios  $q \geq 2$  are close to  $35 \times 10^{-6} \mu\text{m}/\text{Hz}^{1/2}$  [42]. Instead, the values for  $(S_I A_j)^{1/2}$  in GB types with  $q \simeq 1$  are roughly 3 times smaller. Assuming that the cross sectional area of a charge trap is independent of the GB type, the difference in charge trap density supports once more the different nature of the GB barriers.

In the following we will use the Lorentzian spectra sitting on top of a  $1/f$  background (see inset of Fig. 5) to estimate the cross sectional area  $A_t$  of a single charge trap in the barrier: A single charge trap causes the voltage across the junction to fluctuate between two bistable states with an amplitude  $\Delta V$  (see inset in Fig. 6). For large bias currents  $I \gg I_C$ , when the differential resistance is asymptotically reaching the normal state resistance of the junction, we can write for the respective relative resistance change  $\Delta R_N/R_N = \Delta V/V$ . Assuming that the current flow across the junction is homogeneous and the charge trap completely blocks the current flow in a small part of the junction barrier we can determine the charge trap's cross sectional area  $A_t$  from the measured voltage fluctuation amplitude  $\Delta V$

$$A_t = \frac{\Delta R_N}{R_N} A_{qp} = \frac{\Delta V}{V} A_{qp}, \quad (5)$$

where  $A_{qp}$  is the total area of quasi particle transport along the junction. Instead of extracting  $\Delta V$  from a voltage time trace, one can also use the mean squared fluctuation amplitude  $\langle(\delta V)^2\rangle$  determined from a Lorentzian fit of the noise spectrum (see Fig. 6). The two quantities are related via [15]

$$(\Delta V)^2 = \left( \frac{\tau_1}{\tau_2} + \frac{\tau_2}{\tau_1} + 2 \right) \langle(\delta V)^2\rangle. \quad (6)$$

For clearly visible Lorentzians in the measured noise spectra the ratio between the two mean life times is typically in the range from 1 to 10. Hence, we can approximate the fluctuation amplitude within a factor of two

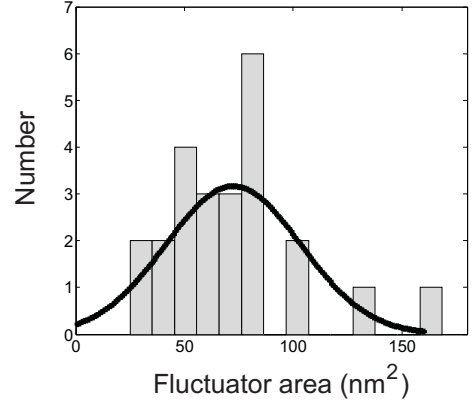


FIG. 8: Histogram showing the effective fluctuator area that was extracted from multiple spectra of 3 different soft patterned junctions in the high bias range. The black curve is a normal distribution with the same mean and standard deviation as the data set.

by  $\Delta V \simeq 2\sqrt{\langle(\delta V)^2\rangle}$  using the root mean squared (rms) fluctuation amplitude extracted from a Lorentzian spectrum (see Fig. 6):

$$S_V^{RTS}(f) = V^2 S_R^{RTS}(f). \quad (7)$$

Together with equation 3 we can extract  $\delta R_N/R_N$  and approximate the cross sectional area of a charge trap:

$$A_t \simeq 2 \frac{\delta R_N}{R_N} A_{qp}. \quad (8)$$

From the results of the previous section we can make the following considerations:

1. The  $I_C$  vs  $B$  measurements have shown that the modulation period corresponds to an effective width close to the nominal width of the junctions. We can therefore assume that the Cooper pair transport is along the whole grain boundary,  $A_{cp} \simeq A_j$ .
2. The fitting of the voltage noise spectral density has shown that  $S_I \simeq S_R$ , this tells us that the area of the superconducting channel is approximately equal to the quasiparticle one,  $A_{cp} \simeq A_{qp}$ .

These two facts imply that the areas of both transport channels are very close to the nominal junction area ( $A_{qp} \simeq A_{cp} \simeq A_j$ ). One can, therefore, use the nominal area, measured by AFM or SEM, in combination with the noise measurement to extract  $A_t$ . Here we also use that the junction thickness  $\simeq$  film thickness (120 nm). We have made this type of analysis for 3 soft patterned junctions and fitted a total of 24 Lorentzians in the high bias range on different spectra. The extracted distribution of  $A_t$  are plotted in Figure 8: We get an average area for the fluctuators of about 72 nm<sup>2</sup>, which is comparable to results found in submicron [001]-tilt YBCO GB junctions [15].



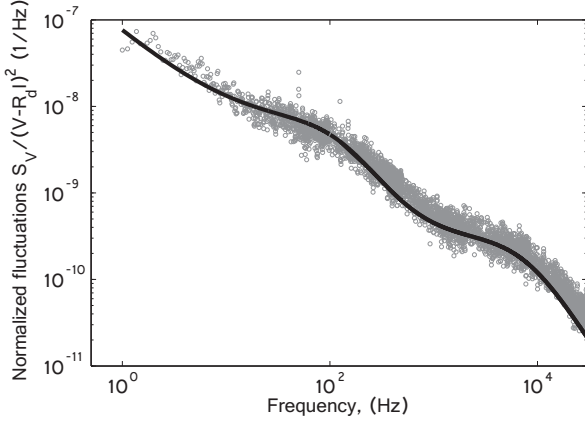


FIG. 9: Noise spectrum (open circles) and fit of two Lorentzians with a  $1/f$ -background (solid line) for one of the soft nanostructured junctions measured at  $I \simeq I_C$ .

In Figure 9 the spectrum at a bias current close to  $I_C$  has been fitted by 2 Lorentzians and a weak  $1/f$  background. Since the contribution from  $R_N$  fluctuations is negligible for this range of currents one can extract  $\delta I_C/I_C$  using equation 3 and:

$$S_I^{RTS}(f) = \frac{S_V^{RTS}(f)}{(V - R_d I)^2} \quad (9)$$

The extracted values for  $\delta I_C/I_C$  and  $\delta R_N/R_N$  are fairly similar in magnitude,  $\delta I_C/I_C$  being at most 3 times larger than the average of  $\delta R_N/R_N$ . This difference could be explained by a spread in the fluctuators area. Indeed the values of  $\delta I_C/I_C$  extracted close to  $I_C$  will certainly come from different two level fluctuators than those generating  $\delta R_N/R_N$  fluctuations at high biases.

### B. Noise properties of conventional junctions

Identical measurements and analysis were carried out for 3 nanosized junctions fabricated by conventional nanolithography. For these samples, at bias currents slightly above  $I_C$  we have observed the presence of strong Lorentzians in the low frequency spectra caused by single charge traps, see Figure 10 (a). This circumstance makes the fitting of the data to equation 4 in the low bias range impossible, therefore preventing the extraction of  $S_I$  and the comparison with  $S_R$ . However, for these junctions we were able to fit the Lorentzian voltage noise spectra for the two different bias ranges, where they are dominated by current fluctuations (close to  $I_C$ ),  $S_I^{RTS}$ , and by resistance fluctuations (far above  $I_C$ ),  $S_R^{RTS}$ , respectively, see Figure 10. Assuming that the average effective area of the charge traps is roughly the same as that extracted from the junctions fabricated by soft nanopatterning we can estimate  $A_{cp}$  and  $A_{qp}$  [43] for the conventionally fabricated junctions. The part of the junction area manifesting Josephson coupling and quasi particle

TABLE II: Total nominal area  $A_j$ , area for the quasiparticle transport channels  $A_{qp}$  and area for superconducting transport channels  $A_{cp}$  (extracted from noise data) for 3 conventionally patterned samples.

Junction nr	$A_j$ (nm <sup>2</sup> )	$A_{qp}$ (nm <sup>2</sup> )	$A_{cp}$ (nm <sup>2</sup> )
Nr 1	50000	31500	1250
Nr 2	30000	14600	9060
Nr 3	30000	22300	160

transport can be approximated by  $A_{cp} \simeq A_t I_C / 2\delta I_C$  and  $A_{qp} \simeq A_t R_N / 2\delta R_N$ , respectively. In the insets of Figure 10 we show the spectral density of the normalized fluctuations multiplied by the frequency. The pronounced difference between the fluctuation amplitudes of the Lorentzians in the critical current and resistance noise spectra by several orders of magnitude clearly manifests the difference in area for the quasi particle and cooper pair transport channels. In table II we summarize the results for 3 conventionally patterned junctions. The average quasiparticle area is 25-50% less than the nominal area. However, the superconducting area varies greatly and for 2 of the junctions it is significantly less than the quasiparticle area. The  $A_{qp}$  extracted from the noise measurements tells us that the grain boundaries, despite losing most of the Josephson properties, still have a quasiparticle transport channel with an average area comparable to the nominal area. The area of the quasiparticle channel does not decrease much in the fabrication process for the conventional junctions, however the resistivity of the channel seem to increase. Evaluating the critical current density based on the effective area across which cooper pair transport occurs results in  $j_C^{eff} = I_C / A_{cp} \simeq 2 - 20$  kA/cm<sup>2</sup>, where  $I_C$  is the critical current of the conventionally patterned junctions. Here it is interesting to note that these values are in the same range as those found in pristine soft nano-structured GB junctions [16]. This fact clearly reflects the strong dependence of the Josephson coupling on the stoichiometry in close proximity (length scale of coherence length) of the GB. The detrimental effect of the ion etching process during the conventional nano patterning seems to locally kill the Josephson coupling rather than inducing a gradual decrease over the whole junction area. The ion beam procedure appears to be an on-off process for the Josephson coupling: the grain boundary region which survives the ion bombardment preserves the same Josephson properties as the untouched soft nano-patterned samples. The overall increase of more than one order of magnitude of the GB resistivity of conventionally fabricated nano-junctions compared to the soft nano-patterned ones can therefore be related to a reduced barrier transparency in the junction regions where the Josephson coupling has been switched off in the milling procedure.

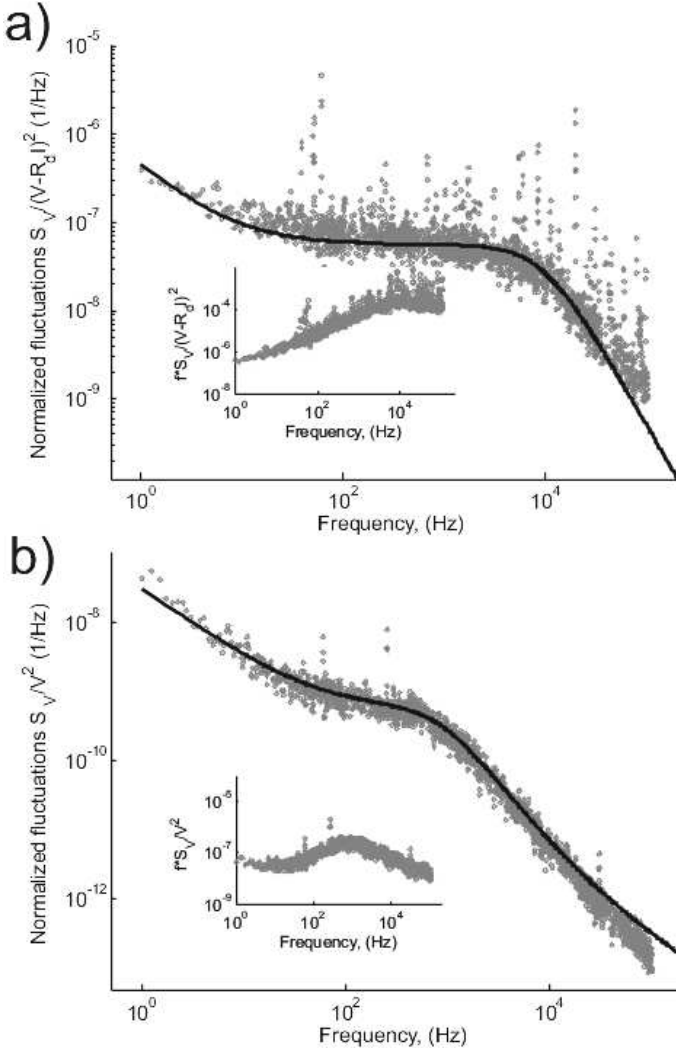


FIG. 10: Noise spectrum (open circles) and fit of a Lorentzian with a  $1/f$ -background (solid line) for a conventionally patterned junction measured at a)  $I \simeq I_C$  and b)  $I \gg I_C$ . The vertical axis show the normalized fluctuations corresponding to a)  $S_I$  and b)  $S_R$ . The insets show normalized fluctuations multiplied by the frequency to emphasize the amplitude of the charge traps.

## VI. SUMMARY AND CONCLUSIONS

To summarize we have compared the electrical transport and noise properties for nanoscaled biepitaxial

YBCO grain boundary Josephson junctions fabricated by two different methods. From electrical transport and  $1/f$  voltage noise properties of soft nanopatterned Josephson junctions with a GB characterized by a rotation of the ab-planes parallel to the interface (large c-axis tunneling component) we can conclude that the GB barrier is very homogeneous and has a SIS character (direct tunneling model). Instead, the noise properties of soft patterned junctions, where the transport is dominated by tunneling parallel to the ab-planes, are in accordance with a resonant tunneling model (ISJ model). From the analysis of two level fluctuators in the barrier, on the other hand, we find that the conventional nanofabrication method severely deteriorates the Josephson properties of the GB. The junction area maintaining Josephson current can on average be much smaller than the nominal area, while the quasi particle transport area is similar to the nominal one. In this case the transport across the GB interface can be well described by the transport model proposed by Miklich [10]. The resistivity in these samples is increased compared to the soft nanopatterned GB junctions. The noise properties of our nanojunctions allows to identify two classes of experiments that one can perform by taking advantage of the specifics of the transport properties:

- 1) to realize quantum bits by employing soft nanopatterned junctions. The pristine grain boundary is an ideal candidate to study the intrinsic source of dissipation in HTS by measuring relaxation and coherence times in a quantum bit.
- 2) to realize devices where charging effects are dominant. The large resistivity values of the conventionally patterned junctions  $\rho_N \simeq 5 \cdot 10^{-7} - 2 \cdot 10^{-6} \Omega \text{cm}^2$  make these junctions good candidates for the realization of all-HTS single electron transistors, which can be used to study possible subdominant order parameters in HTS materials[39].

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- [40] The two formulas for  $\Delta B$  are valid in the short junction limit,  $w_j < 4\lambda_j$ [24], where  $\lambda_j$  is the Josephson penetration depth[26]:  $\lambda_j^2 = \hbar/(2ej_C\mu_0(\lambda_{001} + \lambda_{103} + d))$ . For the soft nanopatterned junctions we get  $\lambda_j \simeq 1.2\mu\text{m}$ . All measured junctions are in the short junction limit since  $w_j < 4\lambda_j$ .
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